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A preliminary study on unbiased volume estimation of resin pockets using stereology to interpret CT-scanned images from one spruce log

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Stereological methods for the volume estimation of resin pockets in saw logs were studied using computed tomography (CT) and image analysis. The Cavalieri theorem was applied for transverse sections and the Pappus theorem was applied for longitudinal radial sections. Stereology applied on wood has to consider both the linear orientation of tracheids and rays, and the circular, lamellar oriented structure of annual rings. The precision of the estimates is illustrated with varying step length between sections, i.e. varying sample size and sampling intensity. To estimate the volume of resin pockets in one log with a coefficient of error of less than 10% requires a step length of 80 mm between transverse sections or ten radial longitudinal sections 18 degrees apart. Here, the resolution of 1.37 × 1.37 × 5 mm overestimated the true volume of resin pockets. Large resin pockets can be detected, whereas detection of small resin pockets, which involved differentiation between resin pockets and compression wood, was difficult with the CT-scanner. This study proves that implementation of stereology on wood can be a good tool for quantitative analysis of resin pockets, which also means that the methods are suited for effective quality control of resin pockets in sawn timber.

Vorläufige Studie zum Erfassen des wirklichen Volumens von Harztaschen mit Hilfe sterologischer Auswertung der CT-Bilder von Fichtenrundholz

Stereologische Methoden zum Erfassen des Volumens von Harztaschen wurden an CT-Bildern mit Hilfe von Bildanalysetechniken untersucht. Für Querschnitte wurde das Cavalieri-Theorem, für Längsschnitte das Pappus-Theorem angewendet. Die Stereologie von Holz muß sowohl die lineare Orientierung der Tracheiden und Holzstrahlen als auch die ringförmige Lamellenstruktur der Jahrringe berücksichtigen. Die Genauigkeit der Schätzung wird anhand verschiedener Schrittweiten der Scans belegt, d.h. durch unterschiedliche Probengröße und Scandichte. Zur Schätzung des Volumens einer Harztasche in einem Rundholz mit einer Fehlerrate unter 10% erfordert eine Schrittlänge von 80 mm zwischen den Querschnitten oder 10 radiale Längsschnitte in Schritten von je 18°. In dieser Studie war bereits eine Auflösung von 1,37 × 5 mm mehr als ausreichend. Große Harztaschen sind gut erkennbar, während kleine Harztaschen, die eine Differenzierung von etwaigem Druckholz erfordern, schwierig mit CT-Scannern zu erfassen sind. Die Arbeit zeigt, daß stereologische Methoden gut zur quantitativen Bildanalyse eingesetzt werden können,. d.h. daß sie sich auch für eine effektive Kontrolle von Schnittholz (im Hinblick auf Harztaschen) eignen.

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1 Introduction

Resin pockets, common in softwoods, are small lenses of resin lying along the annual rings of trees (Fig. 1). The size of resin pockets in Norway spruce varies from a minimum length, width, and thickness of 3.0, 2.5, and 0.5 mm to a maximum of 175, 65, and 7 mm, respectively (Temnerud 1997). Resin pockets are more difficult to predict than knots, their occurrence may cause considerable economical losses in later stages of the industrial processing where single wood details ready for assembling or coating have to be rejected (Temnerud 1996). The prediction of the risk of hitting resin pockets with a random saw plane can be improved by precisely estimating the volume of resin pockets in a certain batch of sawn timber. However, for the practical usage for producers of sawn timber, it is more of interest that the tool or the methods of measurements should be convenient and easy to apply. In addition, the methods should predict precisely the occurrence of resin pockets in various stands of timber.

The differences in x-ray attenuation (measured as CT-number) between resin pockets and the surrounding wood make it possible to detect them using computed tomography (CT) and standard techniques for image analysis (See Fig. 1). Non-destructive scanning devices have been developed and used for anatomical studies of the human body, where stereological methods are commonly used for quantitative assessment of anatomical components in CT-scanned images. The introduction of assumption-free methods in stereology, i.e. methods not based on the assumption of particle shape, size, and orientation, have improved the efficiency of image analysis and offer a

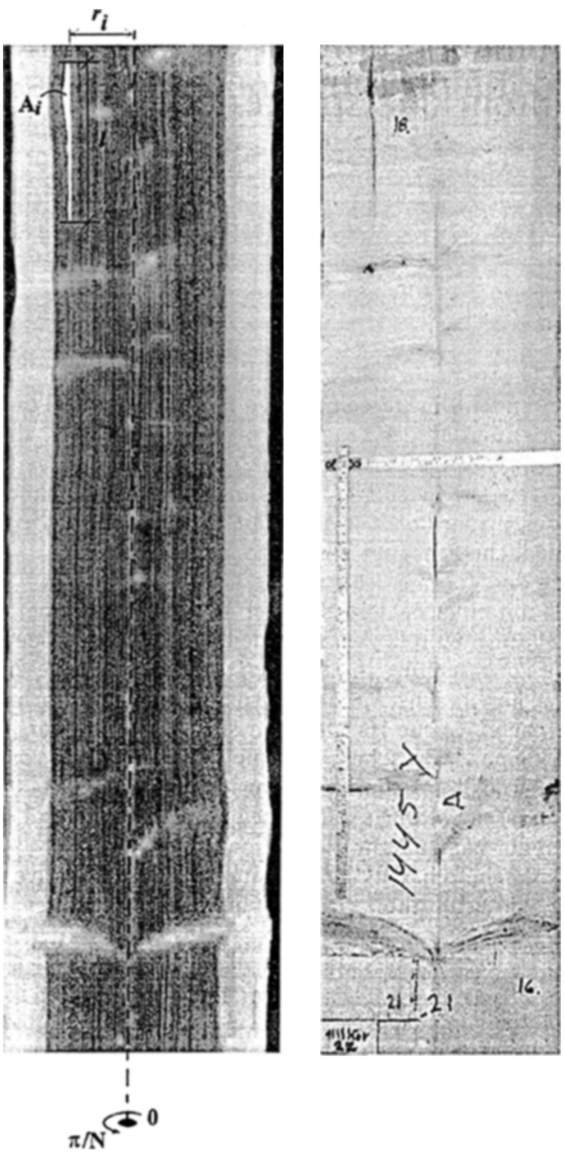


Fig. 1. The resin pockets on the reconstructed radial section from the stack of CT-scanned images corresponds well with the resin pockets on the pith fleck side of the unedged board. The systematic sampling of radial sections is restricted to a location within a half circle of 180 degrees or the radian π times r_i
Bild 1. Form und Position der Harztasche in einem rekonstruierten Radialschnitt (aus einem Vorrat von CT-Bildern) stimmen gut überein mit der tatsächlichen Lage im Mittelbrett aus diesem Rundholz. Die systematische Aufnahme von radialen CT-Bildern ist beschränkt auf einen Halbkreis von 180° oder die Bogenlänge $\pi \times r_i$

greater precision per unit cost (Mayhew & Gundersen 1996). The validity and efficiency of sampling of data in images is determined by the design-based sampling used. An efficient design is to draw a systematic sample of images, objects, or points for measurements (Gundersen & Jensen 1987). A systematic sample in this context always depends on a random start.

The sawing process excludes repeated sampling of differently sawn timber from one saw log. Repeated sampling from the same log described in a stack of CT-scanned images therefore makes it possible to evaluate rules relating to grading of saw logs and sawn timber. The new technique also enables unbiased estimation of the volume of resin pockets in one saw log using common theories in stereology.

Among the stereological methods already in use, the method introduced by Roberts et al. (1993) for unbiased estimation of human body composition by the Cavalieri theorem is similar to that where the volume of resin pockets could be estimated using stem sections from logs. The method presented by Cruz-Orive & Roberts (1993) for unbiased volume estimation of the human bladder with use of coaxial sections is similar to the estimation of the volume of resin pockets using the pith fleck side of the centre yield (longitudinal sections) from logs.

The aim of this study was to use basic stereological principles with adequate sampling technique for the development of convenient methods for the assessment of resin pockets in wood.

2
Materials and methods

The log investigated was the fourth log from the butt (12–16 m up in the tree) in a mature Norway spruce tree (*Picea abies* [L.] Karst.). The green volume of the log was 0.214 m^3 (butt end and top end diameter 28–25 cm, and log length 386 cm). This log was chosen because of the evident high frequency of resin pockets. The log was selected from a pilot study for the planning of a stem bank of spruce logs from experimental forest grounds in Sweden.

The log was scanned in a medical CT scanner (Siemens SOMATOM AR.T.) at Luleå University of Technology, Skellefteå campus. The log was scanned every 10 mm along the length of the log with a 5-mm collimated X-ray beam, which yielded 385 slices (transverse sections of 5-mm thickness) leaving 5-mm gaps between the scans. The scan settings were 110 kV, 50 mA, and 3 s. The reconstructed images were 12-bit images with 512 × 512 pixels. In order to reduce the amount of data handled, these images were converted into 8-bit images containing 256 × 256 pixels. Each pixel represented the average x-ray attenuation coefficient in a volume element (voxel) with the dimensions 1.37 × 1.37 × 5 mm. The reconstruction of the CT-images to longitudinal sections involves a 5-mm extrapolation of the density of the originally scanned voxel, since each longitudinal voxel has the dimensions of 1.37 × 1.37 × 10 mm (Fig. 2, section B-B). The x-ray attenuation coefficient for wood is strongly correlated to wood density (Lindgren 1991a; Lindgren 1991b), and the lightness of a pixel represents the average density of the wood in the corresponding voxel: The lighter the pixel, the higher the density. After scanning, the log was through-and-through sawn into 10 boards of 25-mm thickness parallel to the log axis. The unedged boards were manually examined and the occurrence of resin pockets recorded.

All CT-scanned images (transverse sections) were manually inspected and each resin pocket was marked. The determination of the boundary of each resin pocket was based on experience from earlier manually registered resin pockets. For each marked resin pocket, major and minor axes (length and width), and area and distance from pith were calculated. The *Oxy*-centroid of the resin pocket and the length of the major and minor axes were calculated as the best fitting ellipse (Anon. 1996). Eight data sets from the stack of CT-scanned images were obtained with a successively increasing step length (S = number of transverse sections between samples) of 2, 4, 8, 16, 32, 64, 128, and 256 between transverse sections. For S equal to 2 to 16, all possible starting points were used (sections). For S greater or equal to 32, 16 of all the possible starting were

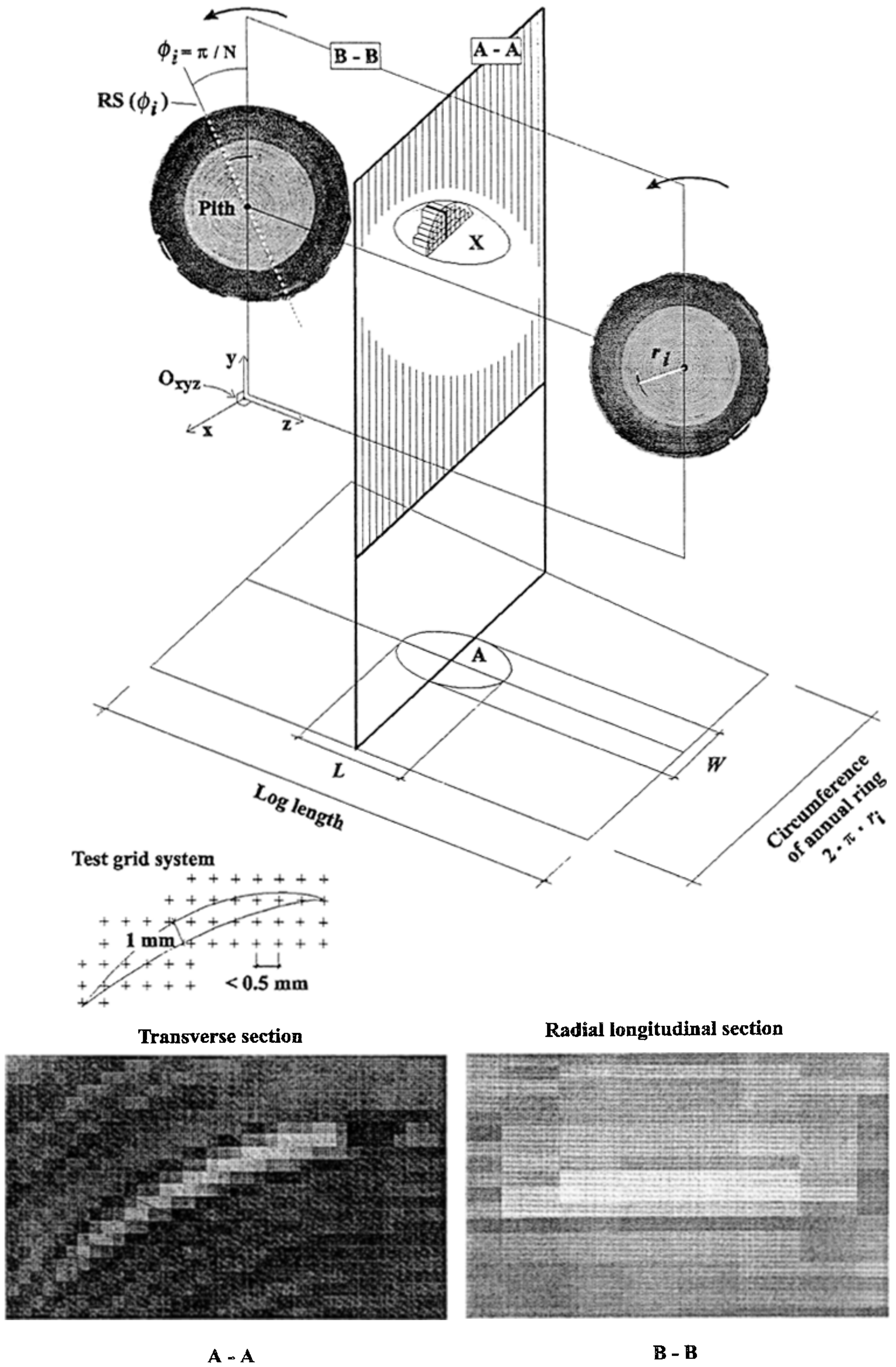


Fig. 2. The systematic sample from the stack of CT-scanned images consists of transverse sections (A-A) and radial longitudinal section (B-B). Above the projection A-A, the distinct contour of the resin pocket in a transverse section is shown with a superimposed test grid. The resin pocket, object X, is described in voxel elements and the projection of the resin pocket gives the projected surface area of A. Here, the measures maximum length (L) and the maximum width (W) are illustrated for the projected area of the resin pocket, which lies in the wooden sheet of one annual ring at the distance r_i from the pith

Bild 2. Die systematisch gesammelten und gespeicherten CT-Bilder bestehen aus je einem Querschnitt (A-A) und einem radialen Längsschnitt (B-B). Über der Projektion A-A (links-unten) ist die Kontur einer Harztasche zu erkennen, darüber ein Schema mit überlagertem Testgitter. Die Harztasche, Objekt X, wird durch Voxel-Elemente beschrieben. Im Bild sind die maximale Länge (L) und Breite (W) für eine spezielle Projektionsebene der Harztasche gezeigt; diese liegt im Brett innerhalb eines Jahrringes beim Abstand r_i von der Markröhre

points used. S = 32 used every second section and started in section no. 2; S = 64 used every fourth section and started in section no. 4; S = 128 used every 8 th section and started in section no. 8; and S = 256 used every 16th section and started in section 16. Step length (S) equal to 2 consisted of two samples with 192 and 193 sections; S = 4 consisted of three samples with 96 and one with 97 sections; S = 8 consisted of seven samples of 48 and one with 49 sections; S = 16 consisted of 15 samples with 24 and one with 25 sections; S = 32 consisted of 16 samples with 12 sections; S = 64 consisted of 16 samples with six sections; S = 128 consisted of 16 samples with three sections; and S = 256 consisted of 8 samples with two and 8 samples with one section.

The radial sections were all reconstructed after the resin pockets had been marked in the stack of CT-scanned images, thereby avoiding differences in judgement between transverse and radial sections in marking the contour of the resin pocket. The first radial section reconstructed from the stack of CT-scanned images was made to simulate the sawn flat side of the unedged board that struck the pith (the pith fleck side). The first radial section started at a distance of 9 mm from the pith in the butt end and increased five pixels in height towards the top of the log, i.e. slightly curved to be able to follow the pith. The positioning of the log in the main headrig saw is dependent on the curve of the log and may thus introduce a bias as the radial sections should be positioned at random. The first radial section should be positioned at random within a predisposed interval, whereas the following radial sections could be systematically positioned with a fixed step length apart. Here, the first radial section was positioned to correspond to the already sawn pith fleck side of the unedged board. From the first radial section, nine new radial sections were sawn clockwise with an 18 degree angle ($\pi/10$) between each radial section. Data sets from the radial sections were obtained with a successively increasing step length (S) of 1, 2, 3, 4 and 10. All possible combinations of starting sections were used. Step length (S) equal to 2 consisted of two samples with five sections; S = 3 consisted of three samples with four sections; S = 4 consisted of two samples with three sections and two samples with two sections; and S = 10 consisted of ten samples with one section.

2.1 Stereology for the volumetry of resin pockets

The standard procedure to describe fractions of objects in a material, e.g. metallic alloy, is to use proportions or ratios V_V, S_V, L_V, and N_V. In this case, V stands for the volume of the object of interest, the resin pocket, and v for the volume of the reference space, the volume of wood in a log (S = Surface area, L = Length, N = Number of objects). The use of ratios or proportions are most effective when the objects of interest are distributed at random in a reference space, and resin pockets cannot be considered to be located completely at random. The stereology applied on wood has to consider that resin pockets are formed along the annual ring of tracheids, which have different geometrical probabilities to be sectioned with radial and tangential sections (Weslien 1993). The sum of the linear intercept L per log length gives the probability to hit resin pockets with a transverse section (Fig. 2). The sum of linear intercept W per length of annual ring gives the probability to hit resin pockets with a radial longitudinal section. Whereas, the length of the annual ring, the circumference, is dependent on the radius (r_i) from the pith to the resin pocket (Weslien 1993).

The term model-based stereology means that the distribution could be modelled by a realisation of a stationary random set. Structures in a reference space that are non-random, i.e. organised with a certain pattern such as organs in a body, have to use design-based stereology, estimating the total measure of the object V cm^3, S cm^2, L cm^1 and N cm^0. Measurements of the total volume of the object are not dependent on measurements of the volume of the reference space, and changes in the volume of wood due to changes in moisture content will therefore not introduce an extra error to the estimates. The description of knots in trees, which are always present and organised in a pattern, resembles the common features and methodological problems as observed for the description of organs in the human body. This makes design-based stereology the reasonable choice. Resin pockets cannot be considered similar to an organ that can be found in every tree, because spruce trees without resin pockets may exist. The occurrence of resin pockets is more pathological and their occurrence may reach epidemic levels in certain trees and stands, e.g. in a similar manner as for tumours or birth-marks. As far as we know, resin pockets are formed preferably in the upper part of the tree and they increase in number with the distance from pith (Weslien 1995; Temnerud 1996, 1997). Thus, the stereological methods applied for the quantification of resin pockets in wood have to consider both the organised pattern of cells within trees, the systematic distribution of resin pockets within trees, and the random location of resin pockets in certain annual rings.

The total volume (V) of resin pockets in the log was first estimated with the Cavalieri estimator (Roberts et al. 1993), using data from transverse sections. The Cavalieri estimator is the distance (T) between transverse sections in the log times the total transected area of resin pockets (A_i) in the whole log (Eq. 1) (Fig. 2). The Cavalieri estimator is unbiased, i.e. its average error is zero, provided that the first section is randomly positioned within an interval of length T:

$$\text{est}_1\ V = T \bullet (A_1 + A_2 + \cdots + A_i)\ \text{cm}^3. \tag{1}$$

Secondly, the total volume V of resin pockets was estimated with the Pappus estimator (Cruz-Orive & Roberts 1993), using data from radial sections. The resin pocket and the log are fixed with respect to an orthogonal reference frame with the axis xyz, where x and y are the radial position in the transverse section (A-A) and z the longitudinal position of the section along the log length (Fig. 2). Origo, $Oxyz$, is positioned in the lower, left-hand corner of the orthogonal reference frame in the butt end side of the log. The log rotates around its central axis, the pith, and the radial section (B-B) is a plane containing the pith (Here, we use radial section for coaxial section). The position of the radial section, RS (ϕ), is determined by the angle ϕ to the vertical y-axis, ($0 \leq \phi < \pi$). A set of systematic radial sections of period π/N (namely a constant angle π/N apart, where N is an arbitrary positive integer) is the set

$$\{\text{RS}(\phi_1), \text{RS}(\phi_2), \ldots\ldots, \text{RS}(\phi_\text{N})\}, \tag{2}$$

where

ϕ_1 is chosen uniformly at random in the interval $(0, \pi/\text{N})$,

$$\phi_i = \phi_1 + (i-1) \cdot \pi/\text{N}, \qquad (i_i = 1, 2, \ldots, N). \tag{3}$$

The Pappus estimator of V is

$$\text{est}_2\ V = \frac{\pi}{N} \bullet \sum_{i=1}^{N} \{r_i \bullet A_i\} \tag{4}$$

(Cruz-Orive 1987), where,
A_i = the area of the transected resin pocket (object X) in a random radial section, $X \cap RS(\phi_1)$,
r_i = the distance from pith to the centroid of the resin pocket $0xy$, $X \cap RS(\phi_1)$. If $RS(\phi_1)$ does not hit X, then we set $A(\phi_i)$ and $r(\phi_i)$ to zero.

2.2
Precision of the estimates

The precision was evaluated by calculation of the coefficient of error (CE) from the empirical results, where CE is the ratio between the standard error (SE) and the mean (CE = SE / Mean). The standard error (SE) is used to avoid confusion with the standard deviation of individual observations (SD). This is because we wanted to estimate a population mean of a parameter describing the object of interest, e.g. the volume of resin pockets in a fixed number of logs from a particular stand, based on a sample of sections. The distribution of resin pockets in the log was considered distributed more or less at random along the stem axis (Fig. 3, top left). The distribution along the x- and y-axis (Fig. 3, top right) was considered random along the circumference of the annual ring but tending to increase to a maximum in intensity about 60–80 mm away from the pith (Temnerud 1996).

3
Results and discussion

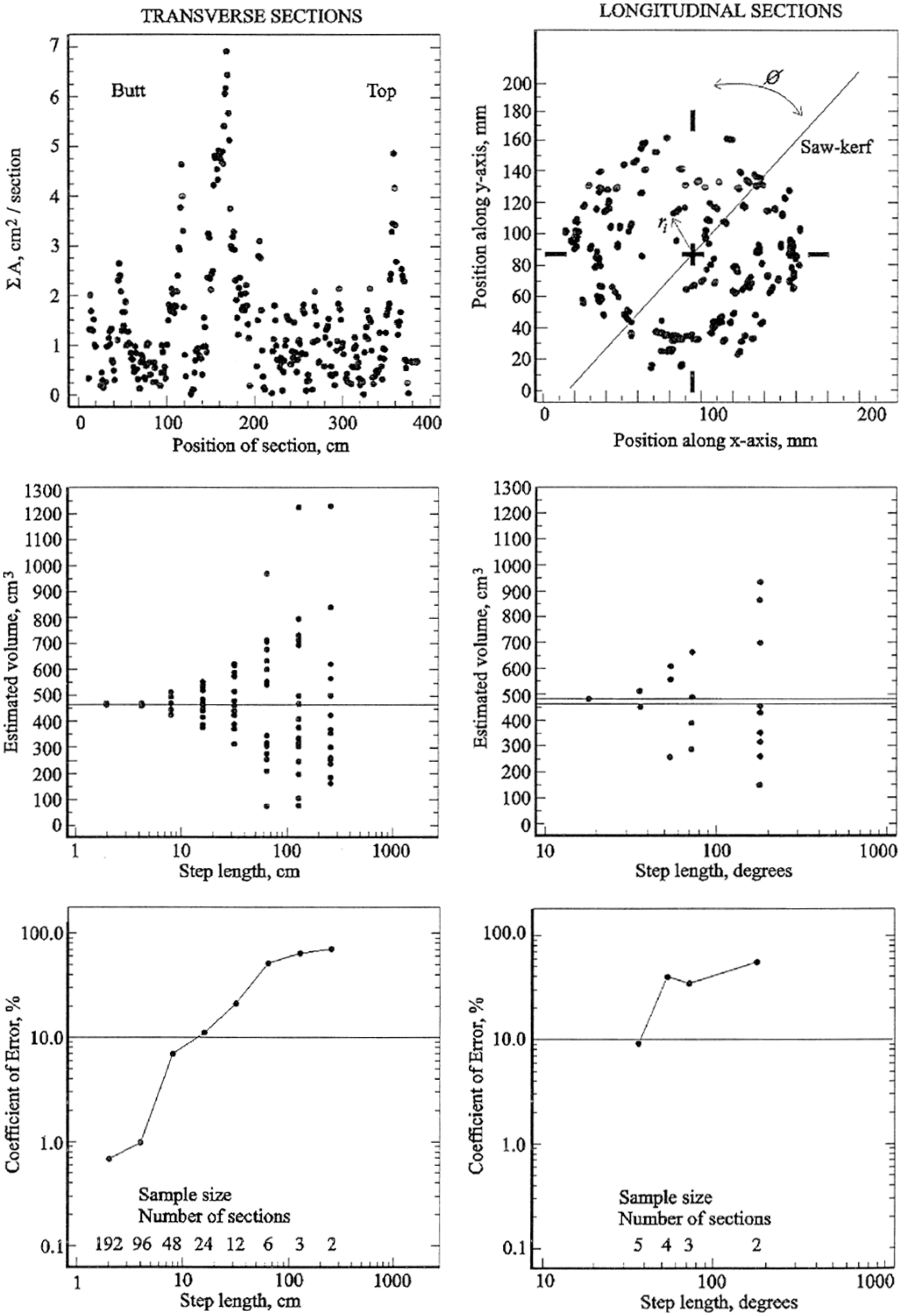
The volume of resin pockets in the log was estimated as 465 cm^3, using the Cavalieri estimator and data from all 385 transverse sections (Fig. 3, middle left). With the Pappus estimator, the volume of resin pockets was estimated as 482 cm^3, using data from all ten radial sections. The discrepancy between the Cavalieri and the Pappus estimator, 465–482 cm^3, can be explained partly by the fact that the ten radial sections represent a smaller portion of wood than the 385 transverse sections, and partly by an introduced bias because of the systematic positioning of the first radial section. The ten observations from individual radial sections (the filled circles) were well balanced on both sides of the estimated volume, which is indicated in the plot with a reference line (Fig. 3, middle right). The 16 observations with one or two transverse sections were also well balanced on both sides of the estimated volume (Fig. 3, middle left), the mean value of the 16 observations was 485 cm^3 (S.E. = 341).

Using the Cavalieri estimator with a step length of 8 cm and repeating the sampling eight times gave a CE of 6.9% (Fig. 3, bottom left), and using the Pappus estimator with a step length of 36 degrees and repeating the sampling five times gave a CE of 9.0% (Fig. 3, bottom right). A large number of sections, 48 transverse- or 5 radial sections, are needed from the log to estimate the volume with a CE of less than 10%, unless the repetitions are increased considerably. However, with optimised step length and repetition of the sampling it is possible to estimate more precisely the volume of resin pockets than the precision of the detection. This is because the uncertainty that some resin pockets never were recorded or misinterpreted as resin pockets may be as large as 10%. In the heartwood and at the sapwood-heartwood interface, it was difficult to judge whether there was a single streak of compression wood along an annual ring or a resin pocket. The similarities in appearance between compression wood and resin pockets made it difficult to distinguish resin pockets around knots. This is because the voxel size used (1.37 × 1.37 × 5 mm) is much larger than the smallest resin pockets that may have a thickness of a few tenths of a millimetre. However, even for large resin pockets, a low resolution (i.e., large voxels) will give a rough picture of the shape and size of the resin pocket. A medical CT-scanner cannot provide satisfactory measures of density in earlywood and latewood in samples with an annual growth ring of less than 3.5 mm (Lindgren et al. 1992). We conclude that the true volume of resin pockets in the log using all the 385 transverse sections was considerably overestimated in this preliminary study.

Despite the fact that small resin pockets were missed out and the true volume was overestimated, 111 resin pockets were traced within the stack of CT-scanned images. The 82 resin pockets recorded on the 10 unedged boards indicate that the major part of resin pockets were detected with the CT-scanner. Because detection of small resin pockets and differentiation between resin pockets and compression wood was difficult with the CT-scanner use of other non-destructive techniques, e.g. magnetic resonance imaging (MRI), may be necessary. The reconstruction of a log and the estimate of the quantity of resin pockets based on inspections of resin pockets on log ends or exhaustively sectioned stem discs is tedious. The CT-scanning technique therefore greatly facilitates the exact positioning of the majority of the randomly positioned resin pockets in a log. Consequently, a stem bank of CT-scanned spruce logs from experimental forest grounds in Sweden can provide a good database for simulations of different cutting alternatives in respect of the majority of the encountered resin pockets on the face of the sawn timber.

For proper volume estimates of resin pockets using a CT-scanner with low resolution, data have to be calibrated to correct for the overestimation. Whenever the interest is to estimate the parameters $V\ cm^3$, $S\ cm^2$, $L\ cm^1$, and $N\ cm^0$, it is recommended to use as high resolution as possible to improve the detection of resin pockets, compression wood, and knots. Sampling fewer sections per log can gain data capacity and time that can be used to increase the resolution in CT-scanned images. Further use of stereology in combination with image analysis would benefit from implementing the technique of point counting on a superimposed test grid (Fig. 2), which is the technique preferred in stereology for estimates of volume or boundary length of curvy objects (Roberts et al. 1993). This is because the decision whether a single point is in or out of the resin pocket is easier than deciding the boundary of the whole area segment that the resin pocket represents.

Stereological principles for quantitative characterisation of wood microstructure are described and used in identification of tree species and for comparing wood structures (Ifju 1983). These principles have, however, not taken into consideration the fact that wood has a linearly orientated structure. The most efficient way of sectioning oriented structures is perpendicular to the orientation of the structure, because the number of transections per area unit test plane (Q/A) estimates the trace length per unit volume ($L_V = Q_A$) and the trace length per area unit of transverse sections (L/A) estimates the surface area per


TRANSVERSE SECTIONS
LONGITUDINAL SECTIONS
Butt
Top
ΣA, cm² / section
Position of section, cm
Saw-kerf
Ø
r_i
Position along y-axis, mm
Position along x-axis, mm
Estimated volume, cm³
Step length, cm
Step length, degrees
Coefficient of Error, %
Sample size
Number of sections
192 96 48 24 12 6 3 2
5 4 3 2

◀
Fig. 3. *Top, left*: All transected areas of the 111 resin pockets, as marked in the 385 CT-scanned images, plotted against the distance along the scanning direction from butt to top. Each transverse section, CT-scanned image, lies 10 mm apart. *Top, right*: The distribution of resin pockets along the x- and y-axis (the annual rings), in which the radial longitudinal sections will cut. *Middle, left*: each dot represents an estimate of the total volume of resin pockets obtained by the Cavalieri formula (Eq. 1) for a given sample with a given number of systematic sections. All averages lie on a common horizontal axis, independent of sample size, which resemble the features of unbiasedness. *Middle, right*: each dot represents an estimate of the total volume of resin pockets obtained by the Pappus estimator (Eq. 4) for a given sample with a given number of systematic sections. The upper horizontal axis represents the value obtained from the ten radial longitudinal sections, whereas the lower horizontal axis is the same as in the middle left figure. *Bottom, left*: each filled circle represents the CE(= SE/Mean) of a Cavalieri estimator of the total volume of resin pockets. *Bottom, right*: each filled circle represents the CE(= SE/Mean) of a Pappus estimator of the total volume of resin pockets
Bild 3. *Oben-links*: Alle Querschnitte der 111 Harztaschen, die in den 385 CT-Scans markiert wurden, sind aufgetragen über der Position der Scan-Richtung (von unten nach oben). Zwischen jedem Querschnitt (CT-Bild) liegen 10 mm. *Oben-rechts*: Verteilung der Harztaschen entlang der x- und y-Achse der Jahrringe. *Mitte-links*: Jeder Punkt bedeutet die Schätzung des Gesamtvolumens an Harztaschen nach dem Cavalieri-Theorem (Gl. 1) für eine Probe mit einer vorgegebenen Schrittweite der Scans. Alle Durchschnittswerte liegen auf einer gemeinsamen horizontalen Linie, unabhängig von der Probengröße (d.h. der mittlere Fehler ist Null). *Mitte-rechts*: Die gleiche Schätzung mit Hilfe des Pappus-Theorems (Gl. 4); die obere horizontale Linie stellt die Mittelwerte der 10 Längsschnitte dar, die untere Linien ist die gleiche wie mitte-links. *Unten-links*: Jeder Punkt repräsentiert den Fehler-Koeffizienten (CE = SE/Mittelwert) der Cavelieri-Gleichung für die Volumenschätzung aller Harztaschen. *Unten-rechts:* die entsprechenden Werte der Pappus-Gleichung

unit volume ($S_V = L_A$) (Fig. 2) (Underwood 1970). A proper description of a piece of wood should consider the linearly orientated structure of tracheids and rays, and include the characteristics in transverse-, radial-, and tangential sections. A problem that arises, especially when estimating the amount of defects in logs using common sawn boards is that a sawn face of a board cuts through wood at different distances from the pith. The outer boards are tangential sections and the boards hitting of the pith are radial sections. The probability that a length section hits a resin pocket is linked to the distance from pith to resin pocket (Weslien 1993). Lacking the measure of the distance from pith to resin pockets, which is difficult to obtain for outer boards, it is difficult to compare groups of outer boards and boards close to the pith and to draw conclusions concerning the frequency of pitch pockets in trees, e.g. from pith to bark (Temnerud 1996). This study shows that it is important to know the distance from the pith to the annual ring in which the resin pocket is formed, i.e. assessing the circumference of the annual ring, for a proper volume estimation of resin pockets from radial sections.

Although, a relatively small volume of the reference space is represented by one radial longitudinal section through a log, its information on occurrence of resin pockets is valuable because no stem sections (transverse sections) are available after processing in sawmills. The pith fleck side of one of the inner centre planks per log is similar to the artificial radial section used in this study (Fig. 1). Using this radial section, human or machine vision-based recordings of resin pockets and the distance from pith to resin pockets could be a convenient method for the assessment of resin pockets in a batch of sawn wood. Instead of measuring the area of resin pockets, the length of resin pockets could be measured. The length of resin pockets estimates the surface area of resin pockets. When analysing the factors related to formation, the surface area may be more interesting as a measure, since it estimates the damage to the cell differentiation zone where the resin pockets are probably formed. But when the measure is used for ranking tree stands in respect of resin pocket incidence, measurements could be restricted to measure the distance from pith to resin pocket (resin pocket radius). The sum of radii estimates the total width of resin pockets (Fig. 2) (Weslien 1993).

As shown in Fig. 3, sampling of a relatively small volume of, the log, could be balanced by an increase in the intensity of sampling. A population of logs from a logging site is usually large, so it is easy to increase the number of logs sampled. The production of one conventional load of sawn timber destined for outdoor panelling consumes 75 logs, which are sawn to 150 boards with the dimensions 47 × 125 mm. Instead of repeating the sampling of one radial section only ten times with a CE of ca. 55% (Fig. 3, bottom right), the repetition could be increased to 75 times or some other higher number equal to the quantity of logs in a conventional load of sawn wood. An estimate of the population mean based on one radial section in each log of a population of 75 logs would lower the coefficient of error, here down to ca. 1–2% exemplified by using the standard deviation from the ten radial sections (263. 14),

$$SE = \sqrt{\frac{263.14^2}{75}} = 5.51 \;;\; CE = \frac{5.51}{465} = 0.012.$$

The formula above estimates the standard error (S.E.) according to the principles of simple random sampling (Scheaffer et al. 1990). The estimated variance in this example originates from only one log. Consequently, it does not include the biological variation between trees and within trees, which could be considerably large (Temnerud 1996). Even if this log contained many resin pockets the maximum number recorded was not more than 16 on one flat side of an unedged board. A number that would be within the range to justify counting all resin pockets instead of inspecting a smaller area of the flat side. The proposed method gives an unbiased estimate of the population mean, but requires that the population of logs is reasonably homogeneous.

If the average radius to resin pockets is the same for two populations the number of transected resin pockets (Q) per radial section for a fixed volume of sawn wood will be an estimate of the sum of widths of the resin pockets. The other measures, S cm^2 and V cm^3, could be estimated from a known average of the population. Knowing the mean width of resin pockets multiplying it by L gives an estimate of S ; knowing the mean thickness of resin pocket multiplying it by S gives an estimate of V. The simplification depends on the following empirical results and theoretical assumptions that should be further investigated (Weslien 1995; Temnerud 1996; Temnerud 1997): The general tendency is that the incidence of resin pockets has its maximum at 60–80 mm away from the pith. The number of resin pockets is strongly correlated to the increase in surface area of resin pockets per volume unit

wood. The size in radial direction is small, 0.9–1.3 mm. All planks in a batch of sawn timber have the same width and the pith fleck side of planks will section through the same interval of radii.

The population of sawn timber analysed could be kept more homogeneous by separating the assortment of logs by origin of stand and position in the tree, i.e. butt-, middle- and top logs. If the population of logs is reasonably homogeneous with the same average radius (r_i) to the resin pockets, it could be enough to record the number of transected resin pockets per radial section. This suggested simplified method is based on a quick, manual measure that could make it possible to count resin pockets on radial sections in the production line without interruptions in the processing.

4
Conclusions
This study proves that common theories in stereology can be used for quantitative analysis of resin pockets in wood. The stereological methods, essentially the science of geometrical probability and statistical sampling theories, provide precise and unbiased methods. They therefore provide a good basis for the construction of convenient methods for an effective quality control of wood defects, e.g. resin pockets in Norway spruce. These methods could be used by producers and consumers of sawn timber for a successively improved prediction of the occurrence of resin pockets in a batch of sawn timber. This study also illustrates how the stem bank of CT-scanned images of populations of saw logs, in spite of limited resolution, can be used to evaluate the precision of various rules for grading of saw logs and sawn timber in the estimate of the quantity of wood defects.

5
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